IB DP BIOLOGY

Theme B: Form and Function

B3.1 Gas Exchange

Revision Notes · Standard and Higher Level

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Original notes prepared for the IB Diploma Programme Biology course (2025 syllabus)

What the syllabus requires

By the end of B3.1 you should be able to work confidently with each of the understandings below. Use this list as a final checklist before the exam. Content marked (HL) is assessed at Higher Level only.

Understanding	You should be able to...
Need for gas exchange	Explain why cells require a supply of O_2 and continuous removal of CO_2, and identify diffusion as the mechanism across the surface.
Properties of exchange surfaces	State and explain the features that make a surface effective: large area, thin, moist, permeable, and served by a maintained concentration gradient.
Fick's law (conceptual)	Relate the rate of diffusion to surface area, concentration difference and diffusion distance.
Human gas exchange	Describe alveolar adaptations, the ventilation mechanism, and the roles of type I and type II pneumocytes.
Three processes distinguished	Separate ventilation, gas exchange and cell respiration clearly.
Leaf gas exchange	Describe the roles of stomata, guard cells and spongy mesophyll, and the trade-off with water loss.
Gas exchange in fish	Describe gills and lamellae and explain why countercurrent flow is efficient.
Ventilation rate (HL)	Calculate ventilation rate from tidal volume and breathing rate, and interpret spirometer / lung-volume data.

> **Exam note:** The command terms used most in B3.1 are *describe*, *explain* and *compare*. Marks are gained by linking each structural feature to the function it serves (a feature named without its purpose usually scores nothing).

1. Why organisms need gas exchange

Every living cell respires. Aerobic cell respiration consumes oxygen and releases carbon dioxide as a waste product:

$$\textbf{glucose} + O_2 \rightarrow CO_2 + \textbf{water} + \textbf{energy (ATP)}$$

Two consequences follow. First, respiring cells continually lower their internal O_2 concentration, so O_2 must be replaced from the environment. Second, the same cells continually raise their internal CO_2 concentration; because dissolved CO_2 forms carbonic acid and lowers pH, it must be removed. **Gas exchange** is the process that meets both needs at a specialised surface.

Diffusion is the mechanism

Gases cross exchange surfaces by **diffusion**: the net passive movement of particles from a region of higher concentration to a region of lower concentration, down a concentration gradient. Diffusion is passive, so it requires no metabolic energy from the surface itself; the gradient does the work.

- O_2 diffuses *into* the organism because its concentration is higher outside (in air or water) than in the respiring tissues.
- CO_2 diffuses *out of* the organism because its concentration is higher in the tissues than outside.

The two gases move independently and in opposite directions across the same surface, each following its own gradient.

The surface-area-to-volume problem

Diffusion alone is fast over micrometre distances but hopelessly slow over millimetres. A single-celled organism such as an amoeba can rely on diffusion across its whole cell-surface membrane because it is tiny: its surface area is large relative to its volume, and no point is far from the surface. As organisms become larger, volume (and therefore O_2 demand) rises faster than surface area, so the body surface can no longer supply the interior. Large or active organisms therefore evolve **specialised gas-exchange surfaces** — lungs, gills or leaves — with a very large area folded into a compact space.

> **Key idea:** Gas exchange exists to solve a surface-area-to-volume problem. The whole of B3.1 is about how different organisms enlarge and maintain a surface across which diffusion can keep up with demand.

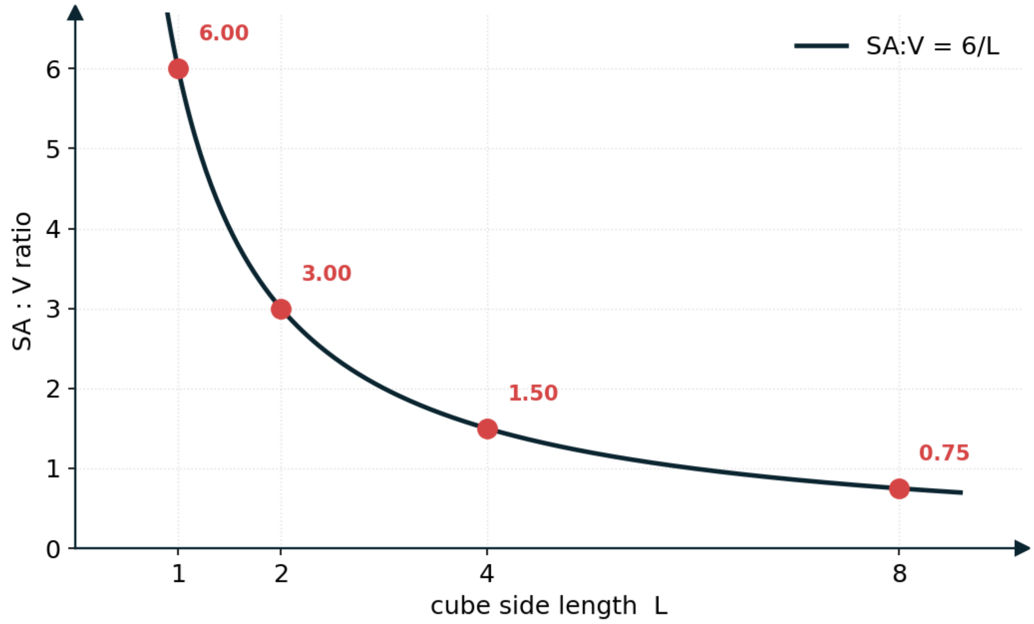

Figure 2. Surface-area-to-volume ratio SA:V = 6/L for cubes of side L = 1, 2, 4, 8 gives 6.0, 3.0, 1.5 and 0.75. As an organism gets larger SA:V falls, so its body surface can no longer supply the interior by diffusion alone.

2. Properties of an effective gas-exchange surface

Wherever gas exchange happens efficiently — in a lung, a gill or a leaf — the same set of adaptations recurs. Learn these five features together with the reason each one raises the rate of diffusion.

Feature	Why it increases the rate of gas exchange
Large surface area	More area means more particles can cross per second; many molecules diffuse in parallel rather than through a bottleneck.
Thin (short diffusion distance)	Exchange surfaces are often only one cell thick, so the path length gases must diffuse across is minimal and diffusion is rapid.
Moist	Gases must dissolve in a thin film of water before they can diffuse across the cell membrane; a moist surface allows O_2 and CO_2 to be exchanged in solution.

Feature	Why it increases the rate of gas exchange
Permeable	The surface is made of thin, permeable cell membranes that allow O_2 and CO_2 to pass freely.
Maintained concentration gradient	Ventilation of the medium and transport of gases by blood or fluid keep fresh supply on one side and remove gases on the other, so the gradient never runs down.

Maintaining the gradient

The first four features are structural, but the fifth is dynamic and is the one most often overlooked. If gases were not constantly replenished and removed, the concentrations on the two sides of the surface would soon become equal, the gradient would fall to zero, and net diffusion would stop. Two mechanisms keep the gradient steep:

- **Ventilation** of the external medium (breathing air in and out of the lungs, or pumping water over the gills) constantly brings fresh O_2 to the surface and carries away CO_2.
- **Transport by blood or tissue fluid** on the internal side carries O_2 away from the surface to respiring cells and brings CO_2 back, keeping internal concentrations favourable for continued diffusion.

Link to Fick's law

These ideas are summarised quantitatively by Fick's law of diffusion. The syllabus treats it conceptually; you should be able to state the relationship and use it to explain adaptations:

$$\textbf{rate of diffusion} \propto \textbf{(surface area} \times \textbf{concentration difference) / diffusion distance}$$

Read directly, the equation says the rate of exchange rises when the surface area is larger, when the concentration difference (gradient) across the surface is greater, and when the diffusion distance is shorter. Every adaptation in the table above changes one of these three terms in the favourable direction.

> **Exam technique:** If a question asks you to *explain* why a surface is efficient, name the adaptation, name the Fick's-law term it affects (area, gradient or distance), and state the effect on diffusion rate. That three-part structure reliably earns full marks.

3. Gas exchange in humans

In mammals the gas-exchange surface is the lining of millions of tiny air sacs, the **alveoli**, deep in the lungs. Air reaches them through the trachea, bronchi and bronchioles; blood reaches them through the pulmonary capillaries.

Adaptations of the alveoli

The alveoli show every feature of an effective exchange surface listed in Section 2:

- **Enormous surface area.** The two human lungs contain roughly 300–500 million alveoli with a combined surface area of about 70 m^2 — comparable to a badminton court — packed into the chest.
- **Walls one cell thick.** The alveolar wall is a single layer of flattened epithelial cells, and the capillary wall is a single layer of endothelial cells, so gases diffuse across only about half a micrometre.
- **Moist lining.** A thin film of fluid coats the inner alveolar surface, allowing O_2 and CO_2 to dissolve and diffuse.

- **Dense capillary network.** Each alveolus is wrapped in a mesh of capillaries, so blood is always close to the air and the gradient is maintained by continuous blood flow.
- **Ventilated.** Breathing constantly refreshes the air inside the alveoli, keeping alveolar O_2 high and CO_2 low relative to the blood.

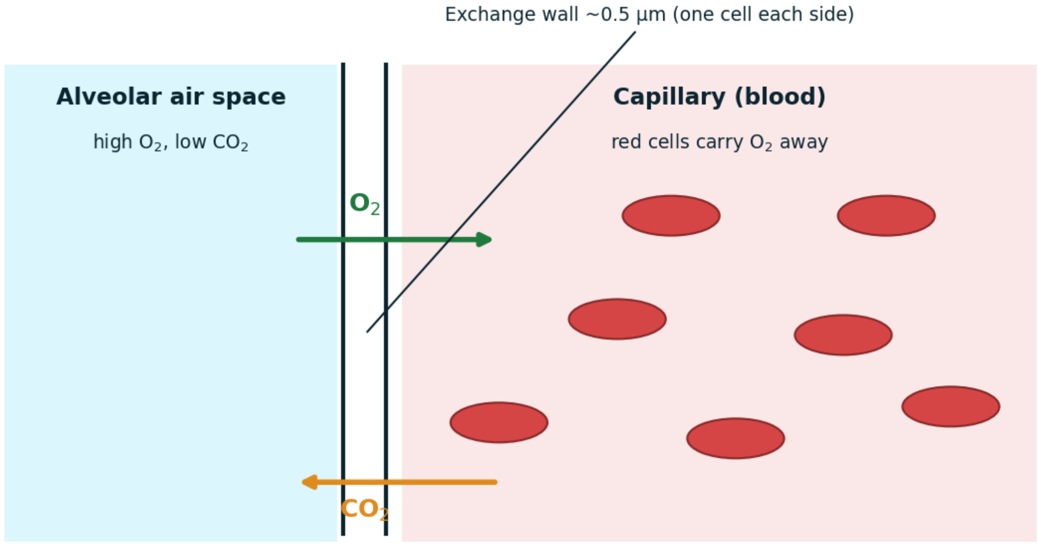

Figure 1. Gas exchange at an alveolus: O_2 diffuses from the air into the blood and CO_2 the other way, across a wall about 0.5 µm thick (a type I epithelial cell plus a capillary endothelial cell). Red cells carry the O_2 away, keeping the gradient steep.

Type I and type II pneumocytes

The alveolar wall is built from two kinds of epithelial cell, called pneumocytes, with different jobs:

Cell type	Structure	Function
Type I pneumocyte	Extremely thin, flattened cells covering most (about 95%) of the alveolar surface area	Form the actual gas-exchange surface; their thinness gives the short diffusion distance gases must cross.
Type II pneumocyte	Smaller, rounded, cuboidal cells scattered between the type I cells	Secrete pulmonary **surfactant**, a phospholipid fluid that reduces surface tension inside the alveoli.

Surfactant lowers the surface tension of the watery film lining the alveoli. Without it, surface tension would tend to pull the moist walls together and collapse the smallest alveoli during exhalation, and a great deal of effort would be needed to re-inflate them. Surfactant keeps the alveoli open, makes breathing easier, and stops small alveoli emptying into larger ones. (Premature babies may lack surfactant, causing respiratory distress syndrome.)

The ventilation mechanism

Ventilation — breathing — moves air into and out of the lungs. Air always flows from high pressure to low pressure, so the body ventilates by changing the volume of the thoracic cavity, which changes the pressure inside it. Two sets of muscles do this: the **diaphragm** (a sheet of muscle below the lungs) and the **intercostal muscles** between the ribs.

	Inspiration (breathing in)	Expiration (breathing out, at rest)
Diaphragm	Contracts and flattens, moving down	Relaxes and domes upward
External intercostals	Contract, pulling the rib cage up and out	Relax
Thoracic volume	Increases	Decreases
Pressure in lungs	Falls below atmospheric pressure	Rises above atmospheric pressure
Air movement	Air is pushed in from outside (down the pressure gradient)	Air is forced out of the lungs

At rest, expiration is largely **passive**: the muscles relax and the elastic recoil of the lungs and rib cage pushes air out. During forced or exercise breathing, the **internal intercostal muscles** and abdominal muscles contract to actively drive air out faster. Note that the muscles work as an antagonistic pair — the external and internal intercostals pull the rib cage in opposite directions.

> **Common misconception:** Muscles cannot “push” air in. Ventilation works entirely by pressure differences created by volume changes. Always explain breathing as: muscle action → volume change → pressure change → air flow.

4. Ventilation, gas exchange and cell respiration

These three terms are easy to confuse and are frequently tested. They are three distinct processes happening at different places and scales.

Process	What it is	Where it happens	Type of process
Ventilation	The mechanical movement of air (or water) into and out of the gas-exchange organ; “breathing”	Lungs / gills as a whole	Physical / mechanical
Gas exchange	Diffusion of O_2 and CO_2 across the exchange surface between the medium and the blood	Alveolar and capillary walls (the surface)	Physical (diffusion)
Cell respiration	The chemical release of energy (ATP) from glucose, using O_2 and producing CO_2	Inside every living cell (mitochondria)	Chemical / biochemical

The logical chain runs: ventilation maintains a steep concentration gradient at the exchange surface → gas exchange (diffusion) supplies O_2 to the blood and removes CO_2 → cell respiration in the tissues uses the O_2 to make ATP and generates the CO_2 that is carried back. Ventilation and gas exchange exist only to serve cell respiration.

> **Common misconception:** “Respiration” in biology means the chemical process inside cells, **not** breathing. Writing “respiration” when you mean “ventilation” (or vice versa) is one of the most common and costly errors in this topic — keep the three words strictly separate.

5. Gas exchange in a flowering plant

Plants also respire in every cell and, in the light, photosynthesise as well. Both processes exchange gases with the atmosphere. The main gas-exchange surface of a plant is the leaf, and the same principles — large area, thin, moist, permeable — apply.

The leaf as an exchange surface

- **Stomata** (singular: stoma) are pores, mostly on the lower epidermis, through which gases enter and leave the leaf.
- **Spongy mesophyll** cells in the lower half of the leaf are loosely packed with a large network of interconnected **air spaces** between them. These air spaces give a very large internal surface area of moist cell walls across which gases can diffuse.
- The moist cell walls lining the air spaces are thin and permeable, so O_2 and CO_2 dissolve and diffuse readily between the air spaces and the cell interiors.

Net gas movement depends on the balance of respiration and photosynthesis. In bright light, photosynthesis exceeds respiration, so the leaf takes in CO_2 and releases O_2 overall. In darkness, only respiration occurs, so the leaf takes in O_2 and releases CO_2. At the **compensation point** the two processes exactly balance and there is no net exchange.

Guard cells open and close the stomata

Each stoma is bordered by two **guard cells** that control whether the pore is open or closed by changing their turgor:

- When guard cells take up water and become **turgid**, their unevenly thickened walls bow apart and the stoma **opens**, allowing gas exchange.
- When guard cells lose water and become **flaccid**, they sag together and the stoma **closes**, reducing gas exchange and water loss.

Stomata are typically open during the day (to admit CO_2 for photosynthesis) and closed at night, when photosynthesis stops.

The trade-off with water loss

Whenever the stomata are open to allow gas exchange, water vapour also escapes from the moist internal surfaces by evaporation and diffusion — this is **transpiration**. The plant therefore faces a fundamental conflict: opening the stomata wide enough to admit CO_2 for photosynthesis inevitably loses water. In dry conditions many plants partly or fully close their stomata to conserve water, which reduces CO_2 uptake and slows photosynthesis. This balance between obtaining CO_2 and conserving water is a central compromise in plant biology.

> **Key idea:** A gas-exchange surface must be moist and permeable — but a moist, permeable surface open to the air unavoidably loses water. In land plants this trade-off is managed by the guard cells opening and closing the stomata.

6. Gas exchange in fish: gills and countercurrent flow

Water holds far less dissolved O_2 than air (about 30 times less), and water is dense and viscous. Fish therefore need a highly efficient exchange surface, constantly ventilated — the **gills**.

Structure of the gills

- Each side of the fish has several **gill arches**, each bearing two rows of thin **gill filaments**.
- Each filament carries many tiny folds called **lamellae** stacked at right angles to it. The lamellae provide a very large surface area and have walls only one cell thick, richly supplied with blood capillaries.
- Fish ventilate the gills by opening the mouth to draw water in and then pushing it out over the gills and through the **operculum** (gill cover), giving a continuous one-way flow of water across the exchange surface.

Countercurrent flow

The key adaptation of fish gills is **countercurrent flow**: across each lamella, the blood in the capillaries flows in the **opposite direction** to the flow of water over the surface. This arrangement is far more efficient than if the two flowed the same way (concurrent flow).

Because water and blood move in opposite directions, blood that is already partly loaded with O_2 meets water that is still fully oxygenated, while blood that is almost deoxygenated meets water that has already given up most of its O_2. At every point along the lamella the O_2 concentration in the water stays higher than in the adjacent blood, so a **diffusion gradient is maintained along the whole length** of the exchange surface, and O_2 diffuses into the blood all the way across. A fish can extract up to about 80% of the O_2 from the water passing over its gills.

Why concurrent flow would be worse

If water and blood flowed in the **same** direction, they would start with a large difference in O_2 concentration, but as blood gained O_2 and water lost it, the two would approach the same concentration — equilibrium — about halfway along. Beyond that point there would be no gradient and no further exchange, so the blood could never take up more than about half of the available O_2.

> **Key idea:** The whole point of countercurrent flow is that it **maintains the concentration gradient along the entire length** of the exchange surface. Say this explicitly — it is the marking point examiners look for.

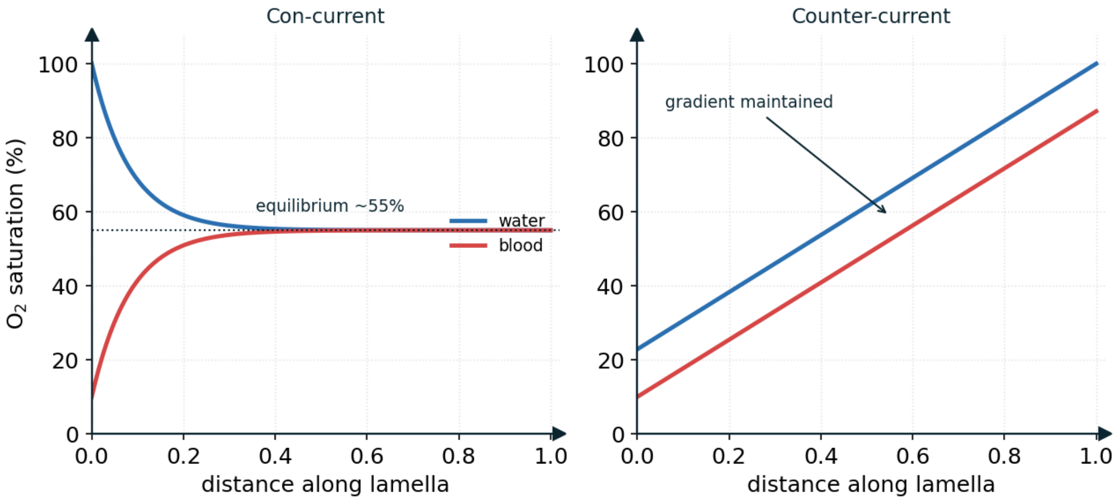

Figure 3. Counter-current versus con-current exchange along a gill lamella. Con-current flow reaches equilibrium near 55 % and caps uptake at about 50 %; counter-current flow keeps the water more oxygenated than the blood the whole length, so blood leaves about 87 % saturated and roughly 86 % of the O_2 is extracted.

7. Comparing gas-exchange surfaces

Although they look very different, the human alveolus, the fish lamella and the plant leaf are variations on the same design. This comparison is a common exam question.

Feature	Human alveoli	Fish gills (lamellae)	Plant leaf (mesophyll)
Exchange surface	Alveolar epithelium	Lamellar epithelium	Moist mesophyll cell walls
Large area from	Millions of alveoli	Many filaments and lamellae	Many cells lining air spaces
Thin surface	Wall one cell thick	Wall one cell thick	Thin, permeable cell walls
Kept moist by	Fluid film + surfactant	Surrounding water	Fluid on cell-wall surface
Gradient maintained by	Ventilation + blood flow	Ventilation + countercurrent blood flow	Diffusion through open stomata; air spaces
Medium	Air	Water	Air

The recurring theme is unmistakable: every efficient exchange surface is large, thin, moist and permeable, and every one has a mechanism for maintaining the concentration gradient. The differences are simply engineering solutions to the same physical problem in air versus water.

8. Countercurrent exchange and ventilation data (HL)

Higher Level extends Section 6 to a more quantitative treatment of countercurrent exchange and adds the analysis of lung-volume (spirometer) data.

Countercurrent exchange, quantified (HL)

Imagine following the water and the blood along a single lamella and reading off the percentage saturation of each. The numbers below are illustrative but show the essential point: in a countercurrent system the water is always more oxygenated than the blood beside it, so the gradient never disappears.

Position along lamella	Water O_2 (% sat.)	Blood O_2 (% sat.)	Gradient (water – blood)
Blood entry / water exit	30	10	20
One-quarter along	50	35	15
Halfway along	65	50	15
Three-quarters along	80	65	15
Blood exit / water entry	100	85	15

A positive gradient exists at every position, so O_2 diffuses into the blood along the whole lamella and the blood can leave almost as saturated as the incoming water. In a concurrent system, by contrast, water and blood would both converge on the same intermediate value (around 55–60%) and exchange would stop once they met, capping uptake at roughly half.

Ventilation rate (HL)

Ventilation is quantified by the **ventilation rate** (also called minute ventilation): the total volume of air breathed per minute. It is the product of the volume of each breath and the number of breaths per minute:

$$\textbf{ventilation rate} = \textbf{tidal volume} \times \textbf{breathing rate}$$

- **Tidal volume** is the volume of air moved in or out in a single normal breath (about 0.5 dm^3 at rest in an adult).
- **Breathing rate** (ventilation frequency) is the number of breaths per minute (about 12–15 at rest).

So a resting ventilation rate is roughly 0.5 × 12 = 6 dm^3 per minute. During exercise both the tidal volume and the breathing rate increase, so the ventilation rate rises several-fold to meet greater O_2 demand.

Interpreting spirometer / lung-volume data (HL)

A **spirometer** records the volume of air breathed over time as a trace of volume against time. You should be able to read the following quantities from such a trace:

Quantity	How to read it from a spirometer trace
Tidal volume	The height of one normal (small) breathing cycle, peak to trough.
Breathing rate	The number of complete breathing cycles counted in one minute.
Ventilation rate	Tidal volume × breathing rate (multiply the two values above).
Vital capacity	The largest possible volume change: from a maximal inhalation down to a maximal exhalation.

> **Exam technique (HL):** When reading a spirometer trace, always check the axis units first. If time is in seconds, convert the breathing rate to breaths per *minute* before multiplying, or your ventilation rate will be out by a factor of 60.

9. Worked examples, skills and pitfalls

Worked example 1 — explain an alveolar adaptation

Explain how two features of an alveolus adapt it for efficient gas exchange. [4]

Answer (using the feature → Fick's-law term → effect structure):

- The alveolar wall is only one cell thick, so the diffusion distance is very short; by Fick's law a shorter distance gives a faster rate of diffusion. (2 marks)
- There are millions of alveoli, giving a very large total surface area; a larger area allows more O_2 and CO_2 to diffuse per second. (2 marks)

Either of moist lining, dense capillary network, or ventilation would also score, provided the effect on diffusion is stated.

Worked example 2 — why countercurrent flow is efficient

Explain why countercurrent flow in fish gills allows more efficient oxygen uptake than if blood and water flowed in the same direction. [3]

- In countercurrent flow the water and blood move in opposite directions across the lamella. (1)
- This means the O_2 concentration in the water is always higher than in the adjacent blood, so a diffusion gradient is maintained along the whole length of the lamella. (1)
- O_2 therefore diffuses into the blood all the way across, so the blood can be loaded to a much higher saturation (up to about 80%) than the roughly 50% limit set by concurrent flow reaching equilibrium. (1)

Worked example 3 — calculate ventilation rate

A student at rest has a tidal volume of 0.45 dm^3 and takes 14 breaths per minute. During exercise the tidal volume rises to 2.5 dm^3 and the breathing rate to 30 breaths per minute. Calculate the ventilation rate in each case and the factor by which it increases. [4]

Use ventilation rate = tidal volume × breathing rate.

At rest: 0.45 × 14 = **6.3 dm^3 min^{-1}**.

During exercise: 2.5 × 30 = **75 dm^3 min^{-1}**.

Factor of increase = 75 / 6.3 ≈ **12 times** greater. Both a larger tidal volume and a faster breathing rate contribute to the rise.

Worked example 4 — interpret a spirometer trace

A spirometer trace shows regular breaths, each with a peak-to-trough height of 0.5 dm^3. In a 30-second window, 6 complete breaths are recorded. Find the breathing rate and the ventilation rate. [3]

Breathing rate = 6 breaths in 30 s = 6 × 2 = **12 breaths per minute** (convert the 30 s window to a full minute). (1)

Tidal volume = height of one breath = 0.5 dm^3. (1)

Ventilation rate = 0.5 × 12 = **6.0 dm^3 min^{-1}**. (1)

Common pitfalls

- **Ventilation is not respiration.** Breathing is a mechanical process; respiration is the chemical release of energy in cells. Never use the words interchangeably.
- **State that countercurrent flow maintains the gradient.** Saying it is “more efficient” is not enough — the marking point is that the gradient is kept up along the whole exchange surface.
- **Remember the stomata water trade-off.** Open stomata that admit CO_2 also lose water by transpiration; this is why plants close stomata in dry conditions.

- **Explain breathing through pressure.** Air moves because volume changes alter pressure — muscles do not push air directly.
- **Name the function, not just the feature.** “Large surface area” earns a mark only when linked to “more diffusion per second”.
- **Check spirometer axis units** before calculating a rate; convert seconds to minutes where needed.

Quick reference

Idea	Statement
Purpose of gas exchange	Supply O_2 for cell respiration and remove CO_2 waste.
Mechanism	Passive diffusion down concentration gradients.
Effective surface	Large area, thin, moist, permeable, gradient maintained.
Fick's law (conceptual)	rate ∝ (area × concentration difference) / distance
Alveolus	Millions of sacs; walls one cell thick; moist; dense capillaries; ventilated.
Pneumocytes	Type I = thin exchange surface; type II = secrete surfactant.
Ventilation mechanism	Muscles change thoracic volume → pressure change → air flow.
Leaf	Stomata + spongy mesophyll air spaces; guard cells open/close; water trade-off.
Fish gills	Filaments + lamellae; countercurrent flow keeps gradient along whole length.
Ventilation rate (HL)	tidal volume × breathing rate

10. Test yourself

Attempt these without notes; full worked answers follow. Questions marked (HL) are Higher Level.

1. State two reasons why organisms need to exchange gases with their environment.

2. List the properties of an effective gas-exchange surface and, for each, explain how it increases the rate of diffusion.

3. Describe how the volume and pressure of the thorax change during inspiration, and name the muscles responsible.

4. Distinguish clearly between ventilation, gas exchange and cell respiration.

5. Explain the trade-off a land plant faces between gas exchange and water loss, and how guard cells manage it.

6. Explain why countercurrent flow allows a fish to extract far more O_2 from water than concurrent flow would.

7. (HL) A person has a tidal volume of 0.5 dm^3 and a breathing rate of 16 breaths per minute at rest, rising to a tidal volume of 3.0 dm^3 and 25 breaths per minute during exercise. Calculate both ventilation rates and the factor of increase.

8. (HL) A spirometer trace shows 5 complete breaths in 20 seconds, each of height 0.6 dm^3. Calculate the breathing rate and the ventilation rate.

Answers

1. To supply O_2, which respiring cells use in aerobic cell respiration to release energy (ATP); and to remove CO_2, the waste product of respiration, which would otherwise accumulate and lower the pH of the cells.

2. **Large surface area** — more molecules diffuse per second (more room in parallel). **Thin** — short diffusion distance, so faster diffusion. **Moist** — gases dissolve before crossing the membrane. **Permeable** — O_2 and CO_2 pass freely through the thin membranes. **Maintained gradient** (ventilation and blood/fluid transport) — keeps the concentration difference steep so net diffusion continues.

3. During inspiration the diaphragm contracts and flattens and the external intercostal muscles contract to raise the rib cage up and out. This increases the volume of the thorax, which lowers the pressure inside the lungs below atmospheric pressure, so air flows in.

4. **Ventilation** is the mechanical movement of air into and out of the lungs (breathing). **Gas exchange** is the diffusion of O_2 and CO_2 across the alveolar surface between air and blood. **Cell respiration** is the chemical release of energy (ATP) from glucose inside cells. Ventilation and gas exchange serve cell respiration.

5. A gas-exchange surface must be moist and permeable to admit CO_2, but such a surface open to the air also loses water vapour by transpiration. So opening the stomata for photosynthesis costs water. Guard cells manage the trade-off by becoming turgid to open the stomata (usually in daylight) and flaccid to close them (at night or in dry conditions), balancing CO_2 uptake against water conservation.

6. In countercurrent flow, blood and water move in opposite directions across the lamella, so at every point the water has a higher O_2 concentration than the blood beside it. The diffusion gradient is therefore maintained along the whole length of the lamella and O_2 diffuses into the blood the entire way across (up to about 80% uptake). In concurrent flow the two would reach equilibrium about halfway, after which no gradient exists and uptake is capped at roughly 50%.

7. (HL) At rest: $0.5 \times 16 =$ **8.0 dm^3 min^{-1}**. During exercise: $3.0 \times 25 =$ **75 dm^3 min^{-1}**. Factor of increase = $75 / 8.0 \approx$ **9.4 times**.

8. (HL) Breathing rate = 5 breaths in 20 s = $5 \times 3 =$ **15 breaths per minute**. Ventilation rate = tidal volume × breathing rate = $0.6 \times 15 =$ **9.0 dm^3 min^{-1}**.